

RESULTS AND DISCUSSION

Phytoplankton

Annual Abundance of Major Algal Groups

From 1986 to 1992, 379 species representing 113 genera from eight divisions comprised the offshore phytoplankton community of Lake Ontario (Tables 2 and 3). Forty-two common species and varieties accounted for 91.1% of the total abundance and 88.2% of the total biomass over the seven-year period (Table 4). Common species for individual years are presented in the Appendix (A1 to A7). Over the seven-year period, the Bacillariophyta contained the greatest number of species (143, Table 2) and the highest relative biomass for the spring (62.2% of the total biomass, range=53.1 to 72.8%, Table 5). Chlorophyta had the second highest number of species (116, Table 2), the highest summer relative biomass during 1987, 1989, and 1990, and the highest average summer relative biomass (29.8% of the total biomass, range=14.9 to 56.9%, Table 6) for the study period. In 1986 and 1991, the Cryptophyta contributed the highest amount of biomass to the summer phytoplankton community while the Bacillariophyta had the greatest relative biomass in 1988 (Table 6). Cyanobacteria accounted for over 40% of the abundance in both spring and summer over the study period (Tables 5 and 6). Stoermer and Ladewski (1978) and Johannsson *et al.* (1985a) observed similar results for 1972/73 and 1981/82 with diatoms and green algae as the dominant groups (Table 7). Mean biomass (mean \pm S.E.) for the spring and summer periods were 0.64 ± 0.07 g/m³ and 0.54 ± 0.03 g/m³, respectively, while abundance (mean \pm S.E.) averaged 2,788 cells/mL and 5,506 cells/mL (Table 8), respectively.

Geographical Abundance and Distribution of Major Algal Groups

Horizontal distribution of phytoplankton in Lake Ontario was documented by Nalewajko (1966), Munawar and Munawar (1975), Stoermer *et al.* (1975), and Stoermer and Ladewski

(1978). The horizontal pattern of phytoplankton in Lake Ontario had a seasonal component related to the thermal bar, whereby, shoreside abundance was considerably greater than offshore abundance (Lorifice and Munawar 1974, Robertson and Scavia 1984). However, Makarewicz (1991) demonstrated that phytoplankton abundance and biomass on the south shore of Lake Ontario were statistically different between nearshore and offshore sites only during meteorologic events that disturbed the sediments.

In general, there was no obvious trend in phytoplankton biomass geographically in the offshore region of Lake Ontario for most years (Fig. 2). In the spring of 1990 and the summer of 1989, biomass was considerably higher at mid-lake stations east of the Niagara River (Fig. 1). At the Division level, Cyanophyta, Cryptophyta, Chlorophyta, Pyrrophyta, and Chrysophyta biomass showed no obvious west/east pattern (Fig. 3). The Bacillariophyta appeared to have a higher biomass in the central and eastern portion of the lake; but this difference was not significantly higher ($P > 0.05$, ANOVA).

Historical Changes in Species Composition

Phytoplankton studies at water intakes in the nearshore region suggest that the phytoplankton community changed considerably with increased abundance from ~ 1920 into the 1970s (Schenk and Thompson 1965, International Joint Commission 1969). Near Toronto for example, mean annual abundance doubled between 1923 and 1954, and at a nearby water treatment plant the average **annual** rate of increase between 1956 and 1966 was over seven times that for the 1923 to 1954 period (Robertson and Scavia 1984). Based on data collected up to 1973, Robertson and Scavia (1984) concluded that Lake Ontario was more severely eutrophic than previously supposed.

Similarly, paleolimnological data indicate Lake Ontario has undergone extensive ecological modification since European settlement (Stoermer et al. 1985). Analysis of algal microfossils in sediments from a 19X 1 offshore Lake Ontario core (Stoermer et al. 1985) showed that in diatom assemblages dominated by oligotrophic Cyclotella species, Melosira (Aulacoseira) islandica and M. italica were displaced in more recent sediments by taxa common to hyper-eutrophic regions and areas of high conservative ion loadings (Actinocyclus normanii f. subsalina, Diatoma tenue var. elongatum, Stephanodiscus binderanus, and S. parvus).

In recent years, a literature pertaining to phytoplankton of the offshore waters of Lake Ontario has developed. Vollenweider et al. (1974) reviewed data on phytoplankton composition and biomass in the Great Lakes including Lake Ontario. Lake-wide investigations of Ontario phytoplankton species composition in 1970 was described by Munawar and Nauwerck (1971) and in 1972/73 by Stoermer and Ladewski (1978). In 1972/73, a comparison of phytoplankton biomass and composition at a midlake and nearshore site was undertaken by Munawar et al. (1974). Johannsson et al. (1985a and b), as part of the Canadian BIOINDEX program, monitored four sites, two nearshore and two offshore, in 1981 and 1982. Also in 1982, Gray (1987) compared nearshore and offshore phytoplankton communities.

Because a different technique was used for enumeration, the data of Stoermer and Ladewski (1978) are not used in many of the comparisons made in this report. There is an obvious difference between the two different data sets collected in 1972/73 (Table 7) that may be attributed to the enumeration procedure, especially in regards to the flagellates (Munawar and Munawar 1975). The phytoplankton samples of Munawar et al. (1974, one offshore sampling site), Johannsson et al. (1985a and b, two offshore sampling sites) and those from this study (seven offshore sampling sites) were all counted by the settling chamber procedure and are thus

comparable. Differences between data sets do exist as to number of stations and seasonal sampling. Where possible, only data from April **and August** offshore sites were compared from various studies.

A change in composition of the phytoplankton community has recently occurred. Pyrrophyta relative biomass decreased from the 1972/73 (3.1%) and the 1981/82 (mean = 21%) period to the 1986 -1992 period (mean = 10.2%, Table 7). Relative biomass of the Chlorophyta and possibly the Chrysophyta appeared to have increased from the early 1970s and 1980s. The high interannual variability for the diatoms, cyanobacteria, and the cryptophytes masks any trend that may exist at the division level (Table 7).

Diatoms have been the dominant division since at least 1970. Offshore communities were dominated by Mclosira islandica (Aulacoseira islandica) in 1970. Typical inshore species, such as Stephanodiscus binderanus, S. tenuis and S. hantzschii were observed only in small numbers in the offshore area (Munawar and Munawar 1982). Dominant diatoms in 1972/73 included Stephanodiscus astraea var. minutula and Mclosira (Aulacoseira) islandica. In addition, species such as Diatoma elongatum, Synedra acus, and Surirella angustata were common, especially in the spring, while cryptomonads, such as Rhodomonas minuta and Cryptomonas erosa contributed very heavily during different seasons (Munawar *et al.* 1974). Stoermer and Ladewski's (1978) 1972 study suggested that S. binderanus and S. minutus together comprised 20% of the algal standing crop.

Considering only the April and August samples of Johannsson *et al.* (1985b), diatoms were the dominant division in 1981 (42.5% of the total biomass) as in 1972, but not 1982 where the cryptophytes predominated (38.4% of the total biomass, Table 7). Offshore diatom communities were co-dominated by Melosira islandica (Aulacoseira islandica), Melosira

binderana (Stenhanodiscus binderanus), Stenhanodiscus astraea v. minutula, and Synedra ulna in 1981, while in 1982 Melosira islandica (Aulacoseira islandica) was the dominant species (Tables 9 and 10). In another study at a midlake site in 1982, Gray (1987) concluded that a decrease in eutrophic species, such as Melosira binderana (Stenhanodiscus binderanus), Stenhanodiscus tenuis, S. hantzschii v. pusilla, and S. alpinus had occurred. Melosira islandica (Aulacoseira islandica) was the dominant diatom at the offshore station in the study by Gray.

In our 19X6-92 samples from April and August, either Stenhanodiscus alpinus or Aulacoseira islandica was the dominant species considering biomass (Table 11). This was also true on an abundance basis with the exception of 1986 when Fragillaria crotonensis and F. capucina were numerically dominant. Although Aulacoseira islandica was the dominant diatom in 1970, 1981/82 and 1986-92, the spring biomass of this species was greatest from 1990 to 1992 (Table 12). Spring relative biomass averaged 16 to 22% in 1981 and 82 and it increased to over 38% of the spring biomass from 1990 to 1992.

Stenhanodiscus alpinus, not prominent in 1972 and 1981/82, was the predominant or second most prominent diatom between 1986 and 1990. This apparent shift in species composition may be a result of classification inconsistencies within the S. astraea entity (Stoermer et al. 1975). It is likely that S. alpinus would be included in the S. astraea complex in previous studies. Stoermer et al. (1975) reported S. alpinus as the dominant winter species in Lake Ontario in 1972, and it was consistently observed in the recent microfossil record (Wolin et al. 1991). If we consider S. astraea to be S. alpinus in 1981 and 1982, biomass in 1981 and 1982 was comparable to biomass after 1986 (Table 12). However, the decrease in biomass of S. alpinus was observed from 1986 (133 mg/m³) to 1992 (15 mg/m³, Table 12). S. alpinus was

considered a eutrophic species by Yang *et al.* (1993), but a mesotrophic species tolerant of moderate nutrient enrichment by Tarapchak and Stocmer (1976).

Stephanodiscus binderanus, a co-dominant in 1981 and a eutrophic species, was also observed in fairly large quantities in 1987 (7.1% of the total spring and summer biomass), 1988 (1.1%), 1990 (2.0%), and 1992 (9.5%). Other prevalent diatoms in certain years included Tabellaria flocculosa (5.4%- 1986; 6.3%- 1987), Fragillaria crotonensis (7.4%-1991), and Stenhanodiscus niagarae (5.7% 1988), another eutrophic species. In regards to diatoms, dominant species composition during this study was similar to that of the 1970s, although biomass of the eutrophic Stephanodiscus alpinus decreased, while the biomass of the oligotrophic/mesotrophic Aulacoseira islandica increased in biomass. Biomass of the oligotrophic indicator Cyclotella ocellata also appeared to increase since 1987 (Table 12).

Both Rhodomonas minuta (1972- 11.0% and 7.0% of the April and July biomass) and Cryptomonas erosa (1972-6.0% of July biomass) were the dominant Cryptophyta in the offshore in 1972 (Munawar *et al.* 1974), in 1981 and 1982 (Tables 9 and 10). During 1986-92, C. erosa was the dominant cryptophyte in the spring and R. minuta was dominant in the summer (Table 12). However, while C. erosa biomass has not changed, summer biomass of R. minuta has decreased from $>79 \text{ mg/m}^3$ in the early 1970s and 1980s to less than 30 mg/m^3 since 1990 (Table 12).

Chrysophytes were generally never observed to be major species in the offshore of Lake Ontario in 1972 and 1981/82 (Table 7). From 1986-92, Chrysophyte biomass averaged 7.6% of the summer biomass, but it increased from 4.1% of the relative summer biomass in 1986 to 12.4% in the summer of 1991 (Table 6). Species of Chromulina, Ochromonas, Chrysococcus

and the Haptophyceae were observed from 1986 to 1992 that were not observed in 1981 and 1982 (Table 12).

Relative spring biomass of the Pyrrophyta decreased from over 11% in 1986 to 4.1% in 1992 (Table 5). Gymnodinium helveticum and Peridinium aciculiferum were dominant in 1972 and 1981/82. These same genera were present and prevalent in the 1986-92 period. The biomass of Gymnodinium in the spring and of Gymnodinium spp., Peridinium spp., and Ceratium hirundinella in the summer was highly variable over the course of the study, but was generally lower than reported for 1972 or 1981-1982 (Table 12).

Trophic Status

Paleolimnological and Lake Data: Wolin *et al.* (1991), in a study of the recent microfossils of Lake Ontario, concluded that abundance of some diatom species associated with grossly polluted areas (hyper-eutrophic) of the Great Lakes, such as Actinocyclus normanii f. subsalsus, Diatoma tenue v. elongatum, Stenhanodiscus binderanus and S. parvus, had decreased while the most recently deposited assemblages are composed of species tolerant of eutrophic conditions, i.e. a recovery, albeit small, of the phytoplankton community from high phosphorus loading had occurred. It is difficult to compare quantitative studies based on actual lake samples versus microfossil studies for a number of reasons. A major problem in evaluating lake samples is that we have, in essence, a snapshot of 1972, 1982, 1986, etc.; not a continuous record as sediment profiles provide. However, it is true that the lake samples from the 1986-1992 period were dominated by Stenhanodiscus alpinus and Aulacoseira islandica which Wolin *et al.* (1991) concluded as being indicative of a less eutrophic situation. With the reduction of ambient phosphorus levels in the 1980s (Stevens and Neilson 1987), eurytopic species, such as Aulacoseira islandica, Asterionella formosa and Fragillaria crotonensis, appear

to have recovered in the microfossil record (Wolin et al. 1991). This trend was reflected in the quantitative lake data, which indicated that the spring biomass of Asterionella formosa, Fragillaria crotonensis and Aulacoseira islandica has increased from 1981 to 1992 (Table 12). The recent lake data support the conclusion from the paleolimnological data that recent depositional assemblages are composed of species tolerant of less than hyper-eutrophic conditions.

Offshore Lake Data: Because of the limited number of studies of the Lake Ontario offshore phytoplankton assemblage prior to 1970, a limited basis for evaluating the long-term effects of eutrophication and the phosphorus reduction program exists. Considering the April and August period, no changes in the ratio of mesotrophic to eutrophic species in Lake Ontario from 1970 to 1986 had occurred (Table 13). After 1987, an increase in the ratio occurred which suggested a reverse in eutrophy. The increase in species designated as M1 in Table 13 is interesting. M1 species are mesotrophic species that are intolerant of nutrient enrichment. M1 species increased in importance after 1987, while M2 species tolerant of nutrient enrichment, and eutrophic species (E) have decreased since 1982. This observation also suggests a reversal in the trophic status, which is similar to the conclusion of Wolin et al. (1991) based on recent microfossil data. From 1986 through 1992, mesotrophic diatom species accounted for approximately $30.4 \pm 5.9\%$ of the phytoplankton biomass while eutrophic diatoms represented less than $10 \pm 1.5\%$ of the phytoplankton biomass (Fig. 4). One oligotrophic species, Cyclotella ocellata, was became more prevalent in the lake after 1987 (Table 12).

Historical trends in offshore phytoplankton biomass indicated a decrease in summer biomass since the 1970s and early 1980s (Fig. 5) that was directly correlated with the decrease in the spring, open water, total phosphorus concentrations (Fig. 6, $r^2 = 0.67$). Because of the

considerable variability in the spring biomass data, no clear trend existed over time (Fig. 5). Using the classification scheme of Munawar and Munawar (1982), average biomass for the spring and summer period during the 19X6-92 period was suggestive of oligotrophic conditions for the offshore waters. However, without a phytoplankton flora indicative of oligotrophic conditions, this conclusion is unreasonable. The classification scheme of Vollenweider (1968), which is based on the maximum biomass of phytoplankton observed during the year, suggested a mesotrophic status of the offshore waters of Lake Ontario in 1987. Similarly, Taylor *et al.* (1987) concluded that Lake Ontario was not eutrophic with a total phosphorus concentration of 12 µg/L and chlorophyll concentration of 6 µg/L.

The designation of the offshore waters of Lake Ontario as mesotrophic based on phytoplankton composition and maximum biomass between 19X6-92 is also unlike the eutrophic status suggested by Wolin *et al.* (1991) for the offshore waters based on recent microfossil studies. This discrepancy between the quantitative lake data and the recent microfossil record perhaps is explainable. Both the recent microfossil record and the modern quantitative lake data suggest an improvement in trophic status based on species composition. Based solely on the species composition of the microfossil record, the lake was classified as eutrophic (Wolin *et al.* 1991), while a number of ecological indicators of the lake (phytoplankton biomass, biomass of mesotrophic species, historic trend in the ratio of mesotrophic to eutrophic species, spring total phosphorus concentrations) suggested mesotrophic conditions.

Species composition by itself in the microfossil record can indicate direction of the eutrophication process and provide relative statements about trophic status, i.e. the lake is more or less eutrophic than previously observed. No classification scheme, such as the biomass-based system of Munawar and Munawar (1982) or Vollenweider (1968), exists for microfossils. The

paleolimnological data and the modern quantitative lake data both suggest an improvement. However, different methods conflict on the magnitude of the improvement.

Trophic Dynamics

As a result of the phosphorus abatement program, ambient levels of spring total phosphorus in the open waters decreased and were correlated ($r^2 = 0.67$) with a decrease in summer phytoplankton biomass from 1970 to 1991, but not spring biomass (Fig. 5 and 6), thereby implying a controlling influence of nutrients. There is some evidence, although not strong, that the phytoplankton community may also have been responding to food-web effects. For example, small unicellular phytoplankton ($< 50 \mu\text{m}$) decreased in relative biomass from 1986 to 1991/92 (76% to 38% - spring, 61% to 51% - summer), while relative biomass of filamentous and colonial algae increased from 1986 to 1992 (5% to 46% - spring, 24% to 38% - summer) (Fig. 7). A decrease in small edible phytoplankton and an increase in colonial and filamentous algae, not as easily eaten by zooplankton, would be expected with an increase in larger zooplankton (Bergquist et al. 1985). In the summer, abundance of several species of Daphnia increased but the abundances were only weakly correlated ($r^2=0.50$) with the decrease in unicellular algae. In the spring, the decrease in large and small unicellular phytoplankton were correlated ($r^2=0.83$) with the increase in the abundance of Limnocalanus macrurus and inversely correlated ($r^2= 0.83$) with filamentous algae (Fig. 8). L. macrurus is omnivorous, effectively feeding on particles from 4 to 24 μm in diameter (Rigler 1972). In Lake Superior, the diatoms Melosira and Asterionella and a chrysophyte, Dinobryon, comprised 80% of the stomach contents of this species (Berguson 1971).